Supplementary Materials

Beam-Based Experimental Validation of FLUKA Predictions for Candidate Spacecraft Shielding Materials

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This supplementary package provides reproducibility material that is supported by the manuscript: a data-reduction/validation workflow figure, machine-readable versions of the material metadata, FLUKA transport configuration, and uncertainty budget, MATLAB scripts for the analysis and figure generation workflows, data dictionaries for the processed datasets, and the prompts used to prepare the conceptual engineering graphics. Point-by-point experimental or FLUKA numerical results that are not explicitly contained in the manuscript have not been fabricated.

Figure S1

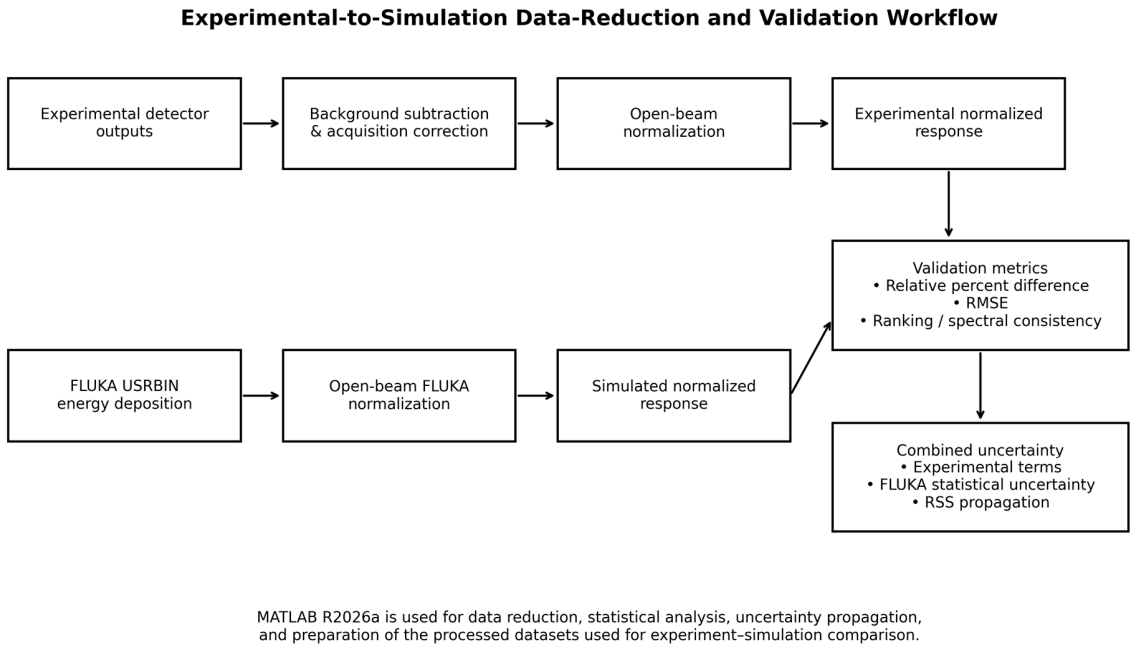


Figure S1. Experimental-to-simulation data-reduction and validation workflow. Experimental detector outputs are background-subtracted and normalized to the corresponding open-beam measurements. FLUKA USRBIN detector-equivalent energy-deposition scores are independently normalized to the open-beam simulation. Experimental and simulated normalized responses are compared using relative percent difference, root-mean-square error, material-ranking and spectral-consistency checks, and combined standard uncertainty. MATLAB R2026a is used for data reduction, statistical analysis, uncertainty propagation, and preparation of the processed datasets.

Table S1. Shielding coupon composition and supplier metadata.

Material	Supplier/location	Nominal composition	Density (g/cm^3)	Thickness (mm)	Areal density (g/cm^2)	Manufacturing route
Aluminum 6061-T6	Industrial Metal Supply, Sun Valley, CA, USA	Al 6061-T6 alloy per supplier certificate	2.70	10	2.70	Wrought plate
HDPE	Interstate Plastics, Sacramento, CA, USA	Polyethylene, (C2H4)n	0.95	30	2.85	Commercial extruded or compression-molded sheet; machined coupon
BNNT composite	BNNT Materials, Newport News, VA, USA	Homogenized BNNT-reinforced polymer composite	1.20	25	3.00	Fabricated composite panel; machined coupon
Boronated polyethylene	Professional Plastics, Fullerton, CA, USA	Commercial boron-loaded polyethylene	1.05	28	2.94	Commercial boron-loaded polymer sheet; machined coupon

Table S2. FLUKA transport configuration and software environment used for the benchmark model.

Parameter	Value used
FLUKA version	4-3.1
Flair version	3.2
Data-processing/statistical software	MATLAB R2026a
Default physics setting	PRECISIOn
Primary particle	Proton
Primary kinetic energy	150 MeV
Beam spatial profile	Uniform circular beam, 2 cm diameter
Angular divergence	0 mrad
Histories per configuration	1.0 × 10^6
Independent cycles	10
Histories per cycle	1.0 × 10^5
Hadron transport threshold	1 keV kinetic energy, or default PRECISIOn transport setting
Electron/positron transport threshold	100 keV
Photon transport threshold	10 keV
Neutron transport	FLUKA multigroup low-energy neutron treatment to thermal energies
Delta-ray production cutoff	100 keV
Nuclear interactions	Default FLUKA hadronic and nonelastic nuclear-interaction models under PRECISIOn
Ion transport and evaporation/coalescence	Enabled using default FLUKA evaporation, fragmentation, and coalescence models
Multiple scattering	Enabled using default FLUKA multiple-Coulomb-scattering treatment
Parallel execution	10 independent single-core jobs, one cycle per job
Random-number seeds	Independent for each cycle/configuration

Table S3. Uncertainty budget used for combined standard-uncertainty propagation.

Source	Evaluation method	Relative standard uncertainty
Detector calibration	Calibration certificate	1.00%
Beam-current stability	Run-to-run monitor data	1.00%
Measurement repeatability	Standard deviation of five measurements	2.5–3.5%
Background subtraction	Propagation of background-count variance	0.50%
Open-beam normalization	Before/after open-beam variability	1.00%
Coupon thickness	Micrometer measurements and propagation	0.50%
Coupon density/composition	Supplier tolerance or sensitivity analysis	1.00%
Sample positioning	Geometry perturbation or tolerance estimate	0.50%
FLUKA statistical uncertainty	Cycle-by-cycle scoring variance	<2%
Detector-response model	Calibration/response-function uncertainty	1.00%
Combined uncertainty	Root-sum-square	3.6–4.7% (material dependent)

Code S1–S4

Code_S1_data_reduction_validation.m. MATLAB script for experimental/open-beam normalization, FLUKA normalization, relative percent difference, RMSE, and RSS uncertainty propagation.

Code_S2_plot_Figure3.m. MATLAB plotting script for Figure 3 using the final processed normalized-response data.

Code_S3_plot_Figure4.m. MATLAB plotting script for the three-panel Figure 4 using the final processed spectral and integrated-count data.

Code_S4_plot_FigureS1.m. MATLAB script for generating the supplementary validation-workflow schematic (Figure S1).

The Figure 3 and Figure 4 scripts intentionally do not embed reconstructed or digitized numerical values. They read the final processed numeric datasets used by the authors. This avoids introducing values that are not explicitly preserved in the manuscript text.

Supplementary Data Files

Data_S1_material_metadata.csv. Machine-readable material, supplier, composition, density, thickness, areal-density, and manufacturing-route metadata.

Data_S2_FLUKA_transport_configuration.csv. Machine-readable FLUKA, Flair, MATLAB, and transport-configuration parameters.

Data_S3_uncertainty_budget.csv. Machine-readable uncertainty-budget entries and relative standard uncertainties.

Data_S4_normalized_response_dictionary.csv. Data dictionary for the processed normalized-response dataset used by Code S1 and Figure 3.

Data_S5_secondary_spectra_dictionary.csv. Data dictionary for the processed spectral-response and integrated-count datasets used by Figure 4.

Data_S6_processed_figure_values. Processed Numerical Values Supporting Figures 3 and 4

Prompts Used for Conceptual Figures

Prompt S1 — Conceptual schematic used for Figure 1

"Create a clean, publication-quality engineering schematic on a white background showing the experimental configuration for a nominal 150 MeV proton-beam irradiation benchmark. From left to right, show the incident proton beam, beam-exit window, 2 cm-diameter collimation aperture aligned with the positive z-axis, shielding coupon mounted at normal incidence in a precision holder, downstream silicon detector active region, and data-acquisition system. Label the distance from the beam-exit window to the collimator as 1 cm, the collimator to the coupon as 5 cm, and the coupon rear face to the detector active plane as 10 cm. Include coordinate axes, a component legend, a key-distance box, and a note that dimensions are referenced between the indicated physical surfaces. Use crisp technical typography and an MDPI-compatible scientific style."

Prompt S2 — Conceptual FLAIR-style geometry graphic used for Figure 2

"Create a publication-quality, three-dimensional FLAIR-style conceptual illustration on a black background of the FLUKA geometry for a 150 MeV proton benchmark. Show, in order along the positive z-axis, a source plane, generic beam-exit window, steel collimator with a 2 cm-diameter vacuum aperture, upstream air transport region, material-dependent shielding coupon, downstream air transport region, silicon-detector active volume, and outer BLACKHOLE transport boundary. Show a red proton-beam centerline and a yellow dashed detector-equivalent USRBIN energy-deposition scoring volume located within the silicon-detector active volume. Label the beam-exit-window-to-collimator distance as 1 cm, the collimator-to-coupon distance as 5 cm, coupon thickness as material dependent, and coupon-to-detector distance as 10 cm. Include a key-distance table, model-and-scoring information box, and region/material legend. Do not assign an undocumented material or thickness to the beam-exit window."

Prompt S3 — Conceptual interaction graphic used for Figure 5

"Create a publication-quality conceptual scientific infographic comparing secondary-particle production during 150 MeV proton irradiation in: (A) Aluminum 6061-T6 and (B) hydrogen-rich or boron-containing materials, including HDPE, boronated polyethylene, and a BNNT composite. For each material class, show an incident 150 MeV proton undergoing electronic energy loss through ionization, elastic nuclear scattering with a recoil nucleus, and a nonelastic nuclear interaction. Show the possible transmitted primary proton and the production of a secondary proton, neutron, de-excitation gamma ray, light ion or nuclear fragment, and recoil nucleus. Show these primary and secondary contributions entering a downstream silicon detector and contributing collectively to the integrated detector response. Include a particle-and-interaction legend and concise material-dependent explanatory notes."

Completed Supplementary Captions/Legends

Figure S1: Experimental-to-simulation data-reduction and validation workflow. Experimental detector outputs are background-subtracted and normalized to corresponding open-beam measurements. FLUKA

USRBIN detector-equivalent energy-deposition scores are independently normalized to the open-beam simulation. Experimental and simulated normalized responses are compared using relative percent difference, root-mean-square error, material-ranking and spectral-consistency checks, and combined standard uncertainty. MATLAB R2026a is used for data reduction, statistical analysis, uncertainty propagation, and preparation of the processed datasets.

Table S1: Shielding coupon composition, supplier/location metadata, density, thickness, areal density, and manufacturing route used in the 150 MeV proton benchmark.

Table S2: FLUKA transport configuration and software environment used for the benchmark model.

Table S3: Uncertainty budget used to calculate the combined standard uncertainty for experiment–simulation comparison.

Code S1: MATLAB script for data reduction, normalization, validation metrics, and uncertainty propagation.

Code S2: MATLAB script for generating Figure 3 from the final processed normalized-response dataset.

Code S3: MATLAB script for generating Figure 4 from the final processed secondary-response datasets.

Code S4: MATLAB script for generating Figure S1.

Data S1: Machine-readable shielding-material and coupon metadata.

Data S2: Machine-readable FLUKA transport configuration and software-environment metadata.

Data S3: Machine-readable uncertainty-budget values.

Data S4: Data dictionary for the processed normalized-response dataset.

Data S5: Data dictionary for the processed secondary-response spectral dataset.

Prompt S1: Prompt used to prepare the conceptual experimental-configuration graphic in Figure 1.

Prompt S2: Prompt used to prepare the conceptual FLAIR-style FLUKA geometry graphic in Figure 2.

Prompt S3: Prompt used to prepare the conceptual secondary-particle interaction graphic in Figure 5.